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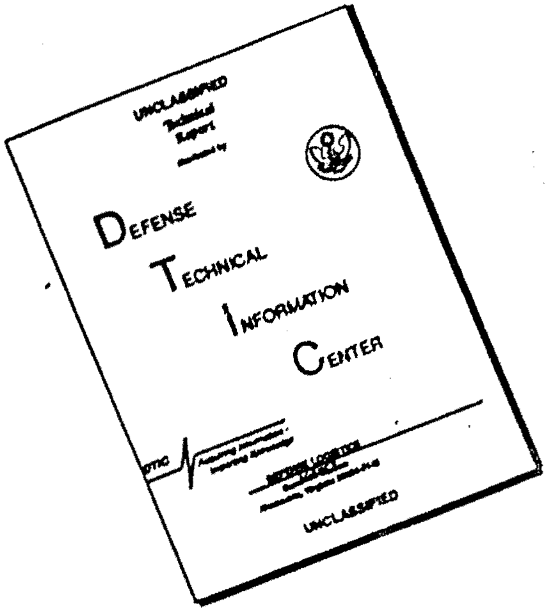

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A STUDY OF THE EFFECT OF FLOATING-ELEMENT MISALIGNMENT ON SKIN-FRICTION-BALANCE ACCURACY

by

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ABSTRACT

An experimental investigation ~~has been~~ was made of the effect of operating a floating-element-type skin friction balance with the element misaligned in the test surface. The misalignment consisted of mounting the element parallel to the test surface, but recessed below or projecting above the surface. A drive mechanism was constructed which permitted traversing the balance and its element through a range of approximately 0.003-in. of recess to 0.003-in. of projection. The effect of misalignment on balance output was determined in a continuous-flow wind tunnel over a Mach Number range of 1.73 to 3.55, at several Reynolds Numbers. The results indicated that any degree of misalignment resulted in a change of balance output. This error in output was slightly larger for the case of a projecting element than for the recessed-element case. No consistent correlation between misalignment error and either Mach Number or Reynolds Number was found.

PREFACE

This report is part of a long range experimental research program conducted by Defense Research Laboratory in the field of turbulent boundary layer flow. An essential part of this program has been the development and use of experimental methods for determining the local shear stress, or skin friction, caused by the motion of the air past solid boundaries. To date the most successful experimental approach has involved the use of the skin friction balance, an instrument that measures directly the skin-friction force on a small movable area of the boundary surface. It has always been known that the accuracy of this method was dependent upon careful installation of the balance instrument, with particular emphasis on flush alignment of the movable sensing element. Unfortunately, alignment of the moving element has often been a very tedious and time-consuming process, made more so by the lack of knowledge regarding the degree of care necessary. Since this was a recurring problem, a decision was made to determine experimentally the effect of misalignment on skin friction balance accuracy. This report contains the results of the experimental program.

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Francis B. O'Donnell, Jr.

TABLE OF CONTENTS

NOMENCLATURE

a = local speed of sound

M = Mach Number $= \frac{U}{a}$

p = pressure

R = universal gas constant

R_θ = Reynolds Number based on momentum thickness

T = temperature

U = mean velocity in direction of flow

y = direction perpendicular to flow

γ = ratio of specific heats at constant pressure and constant volume = 1.4 for air

δ = boundary layer thickness

θ = boundary layer momentum thickness

μ = absolute viscosity

ρ = fluid mass density

τ = shear stress

SUBSCRIPTS

o = stagnation conditions

1 = local condition in boundary layer

I. INTRODUCTION

Drag is an important consideration in the design of modern, efficient airborne vehicles. The influence of drag on the selection of a final vehicle configuration is felt through its effect on fuel consumption and range, the power required for any given speed, and smoothness requirements for surface construction. One component of aerodynamic drag is skin friction, which, as the name implies, is the friction drag resulting from the motion of the aircraft surface (skin) through the air. For laminar flow, this friction has been shown by Newton to be proportional to the viscosity of the air and to the velocity gradient perpendicular to the skin; i.e., $\tau = \mu \frac{du}{dy}$ where τ is the shearing force per unit surface area, μ the air viscosity, u the air velocity and y the perpendicular distance from the skin. The accurate prediction of skin friction drag is essential since the result often determines both the economic and operational feasibility of a new design.

The theoretical determination of skin friction is frequently difficult since many flow variables are involved. Skin-friction theories for laminar flow have been developed, but they are generally for relatively simple aerodynamic shapes. The case of turbulent flow is of more general interest, since turbulent flow exists over a large part of the surface of most aircraft and missiles. There is as yet no general mathematical description of turbulent flows, and even special cases have been difficult to analyze theoretically. Several semi-empirical theories have been advanced for relatively simple turbulent flow conditions, but these depend upon test results to evaluate the constants necessary to apply the theories. No theoretical treatment exists for the more difficult situations involving complex vehicle shapes, compressibility, roughness, and heat transfer. Hence, there is a continuing need for the experimental measurement of skin friction, both to confirm theory and to provide data for cases not amenable to theoretical treatment.

Probably the most accurate method of experimentally measuring skin friction is the use of a floating-element skin friction balance. Its chief advantage is that it is the only device which measures the friction force directly; other methods involve deduction of the force from temperature or pressure measurements. The skin friction balance is relatively simple in construction and produces repeatable data that correlate well with theory and other experimental methods. Skin friction balances typically utilize an element set in an opening in the test surface; the element is held flush with the surface by leaf springs which deflect under the action of a friction force on the element. The element is slightly smaller than the test-surface opening; hence, the element "floats" on springs, inside the opening. It is constrained by the springs to move in the streamwise direction only, and the deflection is measured electrically using a position transducer. Floating-element balances have been used by several investigators in the past, each of whom employed minor design variations to adapt the balance principle to his needs. References 1 to 4 describe some typical designs.

The accuracy of the skin friction balance depends strongly on proper installation of the balance in the test surface. One possible source of installation error is misalignment of the floating element with respect to the surrounding test surface. This misalignment may take the form of projection, depression, or inclination with respect to the test surface or any combination of these three conditions. Such misalignment will subject the floating element to aerodynamic forces other than skin friction, and may also modify the skin friction force itself. A complete theoretical analysis of misalignment error would be very difficult, hence the few error studies made in the past have been experimental in nature. The experimental approach taken by Smith and Walker [Ref. 3] involved making measurements of output at subsonic speeds for a range of positions of a two-inch, disc-shaped floating element. They found that a depression of as much as 0.0005-in. caused no change in the measured surface shear force, while protrusion above the test surface caused noticeable deviations. No quantitative data were given in their report, however. Shutts, Hartwig, and Weiler [Ref. 5] investigated the effect of misalignment upon a one-inch disc type floating element at supersonic velocities. They found that lowering the disc reduced the balance output, but they were unable to make measurements with the disc projecting above the surface. Finally, Dhawan [Ref. 1] writes of the need for an optical degree of flushness, but cites no data to support this assertion. In summary, the experimental data available are fragmentary and inconclusive, and indicate a need for further experimental study of the problem. Since very precise alignment of a balance is a tedious and time-consuming process, it is desirable to know the precision necessary to get satisfactory results. This would serve both to reduce alignment effort and still insure adequate precision.

The purpose of this experimental investigation was to determine the effect of one type of misalignment on skin friction balance output. The particular type of misalignment studied was displacement of the floating element of the balance perpendicular to the test surface. Test equipment was arranged so that a balance could be traversed from a recessed position to a protruding position while remaining parallel to the floor of the test section in a supersonic wind tunnel. The boundary layer in the tunnel used was known to be turbulent. Care was taken to insure that no pressure gradient existed in the test section, and that adiabatic conditions prevailed. Tests were conducted over a Mach Number range of 1.73 to 3.55 for several Reynolds Numbers.

II. APPARATUS AND TEST PROCEDURE

The purpose of this investigation was to determine the effect of element misalignment on the performance of floating-element type skin friction balances. In order to make the results extensively applicable to testing at DRL, it was considered desirable to use a balance configuration typical to those normally used. It was also evident that tests should be made over as wide a range of Mach Number and Reynolds Number as could be obtained. For this reason the DRL variable Mach Number wind tunnel was selected. This tunnel had the additional advantage of being a continuous flow type. An existing skin friction balance having a configuration similar to most DRL balances was selected. An existing displacement indicator was used to measure the element misalignment. The mechanism used to traverse the balance through the desired misalignment range was specifically designed and constructed for these tests. These various components of the test set-up are described in detail below.

A. Wind Tunnel and Instrumentation

The DRL 2 x 2-inch, variable Mach Number, continuous flow wind tunnel, located at the Balcones Research Center of The University of Texas, was used for this test program. The tunnel has a combined flexible nozzle and fixed throat shape which allows test section Mach Numbers in the range of 1.7 to 3.7. The Mach Number change is accomplished by a lead-screw system which changes the throat height. Figures 1 and 2 show additional tunnel details. Four industrial-type compressors are used to operate the tunnel. The test section Reynolds Number is controlled primarily by regulating the tunnel supply pressure. This is accomplished by adding air or removing it from the tunnel circuit. In this way, the amount of air being circulated is controlled.

and consequently the density is also controlled. Manometers are normally used to measure pressures, and operating temperature is measured by means of a bulb-type thermometer. A detailed description of the tunnel is given by Halsell in Ref. 6.

The floor of the wind-tunnel test section was modified to incorporate the mechanism necessary for these tests. In addition to providing an opening for mounting the balance, the floor section was made an integral part of the system which supported the moving part of the balance.

B. Skin Friction Balance

An existing skin friction balance of the same design used in several earlier DRL tests was used in this investigation. Figure 3 is an exploded view of the type of skin friction balance used at DRL; this figure shows the general operating principles of the balance. Figure 4 is a photograph of the working portion of the skin friction balance actually used in this study. The disc-shaped floating element had a diameter of 0.995-in. and an edge thickness of 0.010-in. The test section floor opening had a diameter of 1.005-in., resulting in an annular gap of 0.005-in. when the disc was in the mid-position of its travel.

Two minor modifications were made to the existing balance. A new base was fabricated to attach the balance to the traversing mechanism, and new flexure springs were fabricated. The flexures were made of Havar, a material having a low change in modulus of elasticity with changing temperature. The flexures were designed to give a working force range of 30 millipounds for the balance, a range which was selected to match the expected test conditions. The balance-base modification was necessary to permit movement of the central part of the balance with respect to the case while still maintaining an air-tight seal at the moving joint.

Operation of the balance requires measurement of the deflection of the spring-mounted disc under the action of a drag force. This is accomplished by means of a Schaevitz linear variable differential transformer which was used as a position transducer. A Schaevitz model PC-1 indicator was used in conjunction with the transducer to supply operating power and provide meter indication of the balance output.

Since the purpose of this study was to investigate misalignment effects, it was necessary that particular care be taken to eliminate unwanted misalignments, and to accurately know what the desired misalignment magnitude was. The balance case was installed in the test section floor piece and the entire unit machine ground to insure that the case and floor were perfectly flush. The balance and disc were then installed and the disc was manually aligned to be as flush as possible with the test section floor. Final alignment was accomplished by means of temporarily fixing the disc in place and lapping the disc to the flush condition. Measurements made after lapping was completed, using a device described later, indicated that the disc was flush with the floor within the accuracy of the measurement.

A seal between the balance and the case was necessary to eliminate air flow through the inside of the case, since such flow is known to result in inaccurate balance readings. The seal was accomplished by means of an O-ring lubricated with vacuum grease. Tests made using a vacuum pump indicated that the seal would hold a vacuum of approximately 28-in. of mercury for several hours. The skin friction balance was calibrated by means of a pulley and string system using a weight pan and small weights as seen in Fig. 5. No specific provisions were included for viscous damping of the moving element. The various components of the balance were assembled using screws, and in addition these joints were cemented with an epoxy-type cement to further minimize any possible slippage. The influence of changes in temperature on the operation of the balance were investigated by chilling the balance and allowing it to warm to room temperature. The test-temperature variation was greater than that experienced by the balance during operation of the wind tunnel and the balance output drift was found to be negligible.

C. Elevation Mechanism

One of the most important parts of this work was the design and fabrication of a mechanism to move the skin friction balance in a direction perpendicular to a test surface. The desired limits of motion were from 0.003-in. below the flush position to 0.003-in. above. It was also considered necessary that the traverse mechanism be operable while the tunnel was running, and this requirement introduced the need for an accurate method of correlating disc position and balance output. The final design of the traversing mechanism is shown in Figs. 2, 6 and 7. The skin friction balance was mounted at the center of a steel strap which was fastened at each end to heavy supports machined integral with the test section floor. The strap thus constituted a flat beam which constrained the balance to move on a line normal to the test section floor. Displacement of the balance was accomplished by means of a force which deflected the beam; the force was supplied by means of a lever and screw system actuated from the outside of the tunnel test section. A differentially threaded lead screw was used to deflect a cantilever beam which in turn supplied the final driving force to the balance. The lead screw and cantilever beam were designed to produce a relatively small output motion for relatively large rotation of the lead screw. In this manner it was possible to obtain very small but yet precise deflections of the balance. All parts of the entire mechanism were made as large and stiff as space allowed to minimize unwanted deflections.

The design of a system to remotely indicate disc position during a run was considered. It was concluded that such a system would be quite complex if the desired accuracy was to be maintained. As a result, it was decided to investigate the possibility of obtaining a calibration of balance position in terms of the rotation of the input lead screw. Numerous traverses were made, and measurements of disc position were obtained as a function of drive wheel rotation. It was found that the balance displacement was a linear and repeatable function of the rotation of the input drive wheel, provided the slack in the system was eliminated. This was accomplished simply by approaching each position from the same direction, and avoiding reversal of the drive wheel. It was also established that the mechanical advantage and friction in the system were sufficient to hold the balance in a set position when subjected to the vibration attendant to normal tunnel operation. From these tests it was concluded that balance position could be correlated with drive wheel rotation. This position was measured before and after each traverse, thus accurately fixing the end points of the motion. A linear relation between the end points was then employed.

D. Displacement Gage

Measurement of the disc position, i.e., misalignment, was accomplished using the device shown in Fig. 8. This displacement gage, or misalignment gage, employed a linear variable differential transformer identical to that used in the balance itself. The transformer was considered to be sufficiently precise for measuring the small displacements used in the test. The core of the transformer was threaded onto a small probe, and vertical motion of the probe was detected by the PC-1 instrument previously mentioned. The alignment indicator was calibrated prior to every test measurement using a known displacement.

E. Test Procedure

The usual sequence in making a test run started with setting the nozzle throat for the desired Mach Number, using an available calibration curve. The misalignment indicator was then calibrated and the balance was set in the retracted position, this being 0.0027-in. below the flush position. The disc was then checked to confirm that its surface was still parallel to the test section floor. Since only one PC-1 indicator was available, this indicator was next disconnected from the alignment device and reconnected to the skin friction balance. The necessary adjustments were made and the balance was checked for proper operation. The wind tunnel wall was attached, and the tunnel started at the previously selected pressure level.

Following start-up, the tunnel was operated at the selected pressure for approximately 30 minutes to allow full stabilization of flow conditions and tunnel temperatures. When necessary, the tunnel diffuser was adjusted to eliminate any streamwise pressure gradient in the test section. After stabilization and immediately before starting the balance traverse, stagnation pressure and temperature, test section static pressure, and barometric pressure were read and recorded. The balance was then traversed through its range of motion in steps of approximately .00056-in., with the balance output being recorded at each step. The traverse was made as rapidly as possible to eliminate minor variations in tunnel operating pressure which could not be completely eliminated. At the completion of the balance traverse, the temperature and pressure data were re-read, and any change which occurred was recorded.

After tunnel shut-down, the balance was calibrated using the pulley and weight system previously described. Next, the alignment indicator was re-calibrated, and the final disc position measured and recorded. The final step was to check the linearity of the skin friction balance traverse mechanism by returning to the original recessed position and repeating the traverse; at each step, the actual disc position was measured and recorded, and the data plotted to ascertain its linearity.

III. DATA REDUCTION

The test program produced the following data: stagnation pressure (p_o), stagnation temperature (T_o), test section static pressure (p), disc location before and after each traverse, and Schaevitz PC-1 meter readings of skin friction balance output at each traverse step. The reduction of these data to their final forms required that certain assumptions be made. In arriving at tunnel flow conditions, it was assumed that the air obeyed the equation of state for a thermally perfect gas, that the flow was isentripic, and that the static pressure normal to the direction of flow was constant across the test section. In determining disc location, the assumption previously mentioned regarding the uniform motion of the traversing mechanism was made. The methods of data reduction used are discussed below.

A. Wind Tunnel Flow Conditions

The assumption of the isentropic flow of a perfect gas permits using the following relationship between static pressure and stagnation pressure:

$$\frac{p}{p_o} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{-\frac{\gamma}{\gamma-1}} \qquad \text{(Eq. 1)}$$

From this relation the free stream Mach Number at the test section was determined using measured values of static and stagnation pressures.

Free stream temperature at the test section was found using the following relation:

$$\frac{T}{T_o} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{-1} \qquad \text{(Eq. 2)}$$

Viscosity was then calculated using Sutherland's formula:

$$\mu = 2.270 \left(\frac{T^{\frac{3}{2}}}{T + 198.6} \right) \times 10^{-8} \qquad \text{(Eq. 3)}$$

Density at stagnation conditions was found from the perfect gas relation

$$\rho_o = \frac{p_o}{RT_o} \qquad \text{(Eq. 4)}$$

Density at free stream conditions was then determined from

$$\frac{\rho}{\rho_o} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{-\frac{1}{\gamma-1}} \qquad \text{(Eq. 5)}$$

Free stream velocity was determined from the expression

$$U = Ma \qquad \text{(Eq. 6)}$$

where a is the free stream sonic velocity found from

$$a = \sqrt{\gamma RT} \qquad \text{(Eq. 7)}$$

Momentum thickness, θ, is defined by the expression

$$\theta = \int_0^\delta \frac{\rho_1 U_1}{\rho_\infty U_\infty} \left(1 - \frac{U_1}{U_\infty}\right) dy \qquad \text{(Eq. 8)}$$

where the subscript ∞ refers to free stream conditions, and where the subscript 1 refers to local values in the boundary layer. Since boundary layer surveys were not a part of this program, it was necessary to rely on the work of previous investigators to determine momentum thickness. Three previous DRL reports were utilized: those of Stalmach [Ref. 7], Moore [Ref. 8], and Hill [Ref. 9] all of whom made the measurements necessary to calculate the momentum thickness. These three investigations were made in the same tunnel as the present work, and under similar conditions. Momentum thicknesses were obtained for this report by adjusting the earlier data to the present test conditions.

Reynolds Number based on momentum thickness was defined as

$$R_\theta = \frac{\rho U \theta}{\mu} \qquad \text{(Eq. 9)}$$

where the density, viscosity, and velocity are based on free stream conditions and found as described above.

B. Skin Friction Data

Skin friction balance output readings were converted directly to skin friction force in millipounds using the calibration made immediately after each test run. The traverse position of the floating element corresponding to each skin friction balance data point was found by assuming uniform movement between measured limits, as discussed in Section II.

IV. DISCUSSION OF RESULTS

A. Accuracy

The accuracy of the calculation of Mach Number for each run was determined by the accuracy of the measuring equipment and by the degree to which steady-state tunnel operating conditions were attained. Perhaps the best indication of the overall accuracy is given by the repeatability of several measurements made with a fixed nozzle setting. Typical scatter from instrumentation and operating conditions resulted in a variation of approximately ± 5% in the calculated values of Mach Number obtained with one nozzle setting and several values of operating pressure. In a similar manner it was found that the scatter in Reynolds Number per foot was also approximately ± 5%. Since the momentum thickness was obtained by correcting the results of previous investigators to apply them to the present test conditions, an accuracy of ± 10% is estimated for the Reynolds Number based on momentum thickness.

Several factors also enter into the accuracy of skin friction measurements. The accuracy stated by the manufacturer for the Schaevitz PC-1 indicator is 1% of full scale. Changes in operating temperature have both an electrical and mechanical effect on balance output. As previously discussed, the effect of temperature change on the no-load reading of the balance was found to be less than ± 2%. Similarly, thermal oven checks of balances similar to the one used for these tests have shown that the slope of the calibration curve changes approximately 1% for each 10-degree change in operating temperature. By computing the test section wall recovery temperature, it was found that the maximum temperature change during a run would have been approximately 50-degrees F., the difference between room and recovery temperatures. However, the design of the balance serves to insulate the working portions from rapid changes in temperature, and the calibrations made after each run were performed as rapidly as possible to minimize the effect of temperature changes. For this reason, it is estimated that the error due to changes in temperatures was not over 1%. This conclusion is reinforced by the fact that the balance calibration curves were linear within 1%. If a temperature effect had been present, it would have resulted in a non-linear calibration.

Another factor which may have influenced the balance accuracy was the presence of oil in the wind tunnel. The design of the air supply compressors results in some oil vapor in the air, and the filters are not completely efficient in removing all this oil. Although the oil was readily visible in the test section, no measurable effects at any disc position were noted and indications are that it had no influence on the results.

The total error which might be expected to occur from all the sources discussed above is ± 7%. However, it is estimated that the actual accuracy of the majority of the balance measurements is ± 4%.

The nature of the displacement indicator is such that it has better accuracy in making relative measurements than in determining absolute values. Thus when the indicator was used to measure a displacement, the accuracy of measurement was not as good as when the indicator was used to measure a change in displacement. The accuracy of any specific displacement measurement is estimated to be approximately ± 0.0002 inches. Numerous calibrations of the traversing mechanism yielded an average accuracy of 1%, in terms of deviation from a linear calibration. Thus the difference between two displacement measurements is estimated to be accurate to 1%.

B. Presentation of Results

The results from all the tests are presented in Tables I through V. The balance output corresponding to various displacements is given in millipounds of drag force. In the flush position, the drag force has only a skin friction component; when misaligned, the balance is subjected to wave and pressure drag as well. For this reason, use of the term "skin friction" has been avoided. The results are also presented in Tables I through V in normalized form, referenced to the value obtained with the element in the flush (aligned) position. These normalized values are more directly indicative of the error resulting from misalignment, if it is assumed that the reading obtained when the balance was flush was the correct one. Figures 9 through 15 present these data graphically by showing the normalized balance output as a function of misalignment.

C. Discussions of Results

Although the test data as presented in Figs. 9 through 15 show some scatter, the overall trend is clear. Based on comments made by earlier investigators, it was expected that there would be a small range of recessed misalignments which would not produce appreciable errors in balance performance. The present test data show that this is not true, but rather that any misalignment however small will result in a corresponding error in balance output. In general the magnitude of the error produced by a recessed disc is not as large as that resulting from a disc having equal projection. The error curve is continuous through the zero alignment position, however, and it is obvious that precise alignment is necessary for proper balance performance. The slight scatter and minor inconsistencies in the plotted data probably are the result of efforts to traverse the balance in very small steps, which required that the traversing mechanism be operated very near its limit of accuracy. The region of main interest is that where the displacements are small, and the corresponding errors are also small. In this region, the results are highly satisfactory. The error is almost linear with displacement and is approximately 1% for each 0.00025-in. misalignment. Since it is normal practice at DRL to endeavor to keep the overall skin friction balance accuracy to within 2%, it is obvious that very precise alignment is necessary.

Consideration of Figs. 14 and 15 indicates that no obvious effect of Mach Number can be seen. The variation among the several runs is believed to be more a result of variations in tunnel operation and equipment performance; if a Mach Number effect is in fact present, it is unquestionably small. Similarly, a consideration of Figs. 9 through 13 indicates that any effect of Reynolds Number is quite small. The results vary somewhat with Reynolds Number, but there does not appear to be a consistent pattern in the variation.

Some observations concerning the relative significance of displacement and measurement errors seem pertinent at this point. On a smooth surface a misalignment error of 0.0002-in. can be felt by hand; an error of 0.0005-in. can be readily seen. Hence, unintentional installation errors greater than 0.0005-in. seem unlikely, and the average error in measured force noted for such misalignment was less than 2%. The test equipment accuracies discussed above are thought to be of secondary importance, since the validity of the test results is dependent upon relative changes, not absolute measurements. Each traverse of the disc was conducted after flow and temperature conditions had stabilized, and took less than ten minutes. Under these test conditions the inaccuracies in absolute measurements by the balance and in the traversing mechanism calibration would not invalidate conclusions based on relative changes.

A comparison of the data obtained in this investigation with previous misalignment studies indicates general agreement. The tests of Shutts, Hartwig and Weiler [Ref. 5] were conducted in a continuous flow supersonic tunnel with flow conditions similar to those of the present investigation but with less sophisticated instrumentation. They found that lowering the floating disc 0.001-in. reduced the balance output by 3.1%, a result which compares favorably with data obtained in this report. Shutts, Hartwig, and Weiler were not able to make measurements with a projecting disc. Smith and Walker [Ref. 3] made misalignment studies at subsonic flow conditions using a null-type balance. They found that "...the surface of the floating element could be depressed as much as 0.0005-in. without any change in the surface shear. However, when the element protruded above the surface of the wall, there were noticeable deviations in the measured shear force." They also state that the accuracy of the skin friction balance used was believed to be ± 2%. Since the present study indicates that the average error for a depression of 0.0005-in. is -2%, it is reasonable to suppose that Smith and Walker would not attempt to distinguish between measurements that fell within the expected accuracy of their instrumentation.

It should also be noted that both of the previous investigations discussed above were of the nature of minor degressions from other projects. Neither utilized a traversing mechanism for the skin friction balance, and it would seem likely that the data suffered from the scatter expected when an attempt is made to exactly repeat operating conditions.

An attempt was made to devise a theory to predict the variation of measured force with disc position. It was hoped that such a theory would match the experimental data and yet be general in nature. In the case of the recessed disc, the approach taken was to allow for wake effects by reducing the effective disc area exposed to a constant shear stress. In the projection case, the only additional aerodynamic drag component considered was that of dynamic pressure upon the frontal area of the disc. In neither case could the theory be made to conform with experiment without unreasonable adjustment. The conclusion drawn from this study was that factors such as compressibility and three-dimensional flow are of major importance to the problem and make its analytic solution beyond the scope of this report.

V. CONCLUSIONS

An investigation has been made of the effect of operating a floating-element-type skin friction balance with the element misaligned in the test surface. The misalignment consisted of mounting the element parallel to the test surface, but recessed below or projecting above the surface. Using as a reference the balance reading obtained when the element was flush with the test surface, it was found that any misalignment resulted in a change in balance output. When the element was recessed below the test surface, the balance reading was low; when the element projected above the surface, an excessively high reading was obtained. For misalignments in the range of 0.001-in., it was found that the error was approximately 1% for each 0.00025-in. of misalignment. The error became progressively larger for larger misalignments. For the range of conditions investigated, the error caused by misalignment did not appear to be a function of Mach Number or Reynolds Number.

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EFFECT OF MISALIGNMENT ON BALANCE PERFORMANCE FOR SEVERAL REYNOLDS NUMBERS AT M = 1.73

TABLE I

Run	14		15		16		17	
Mach	1.71		1.73		1.74		1.73	
R_θ	4560		6720		10200		12700	
Disc Position	Force (Milli-pounds)	Percent Level Value	F	%	F	%	F	%
+0.00300					21.95	120.2		
+0.00250	13.60	113.2	16.75	115.5	21.55	118.0	25.50	118.0
+0.00200	13.10	109.2	16.50	113.8	20.95	114.8	24.85	115.1
+0.00150	12.70	105.9	16.10	111.0	20.20	110.8	23.95	110.9
+0.00100	12.40	103.3	15.50	106.9	19.55	107.1	23.00	106.5
+0.00075	12.30	102.5	15.20	104.9	19.20	105.2	22.60	104.7
+0.00050	12.20	101.7	14.95	103.1	18.85	103.3	22.20	102.8
+0.00025	12.10	100.8	14.70	101.4	18.55	101.7	21.80	101.0
Flush	12.00	100.0	14.50	100.0	18.25	100.0	21.60	100.0
-0.00025	11.95	99.5	14.40	99.3	18.10	99.1	21.40	99.0
-0.00050	11.90	99.2	14.25	98.2	18.00	98.6	21.25	98.4
-0.00075	11.85	98.7	14.15	97.5	17.95	98.3	21.15	97.9
-0.00100	11.75	97.8	14.00	96.5	17.90	98.0	21.10	97.6
-0.00150	11.40	95.0	13.80	95.2	17.55	96.1	20.65	95.5
-0.00200	11.00	91.7	13.60	93.8	17.10	93.7	20.00	92.5
-0.00250	10.70	89.1	13.25	91.3	16.50	90.4	19.35	89.6

EFFECT OF MISALIGNMENT ON BALANCE PERFORMANCE FOR SEVERAL REYNOLDS NUMBERS AT M = 2.23

TABLE II

Run	9		10		11		12		13	
Mach	2.25		2.20		2.24		2.23		2.24	
R_θ	3115		6570		9460		11780		14000	
Position	Force (Milli-pounds)	Percent Level Value	F	%	F	%	F	%	F	%
+ .00300									26.00	116.1
+ .00250	9.25	114.2	13.55	118.3	17.25	111.3	20.85	111.8	25.30	113.0
+ .00200	8.90	110.0	12.95	113.1	16.70	107.8	20.25	108.6	24.50	109.3
+ .00150	8.65	106.9	12.25	107.0	16.20	104.5	19.50	104.6	23.70	105.8
+ .00100	8.55	105.7	11.65	101.8	15.85	102.3	19.00	101.9	22.85	102.1
+ .00075	8.45	104.3	11.55	100.9	15.75	101.7	18.85	101.1	22.60	100.9
+ .00050	8.30	102.5	11.50	100.4	15.70	101.2	18.80	100.7	22.50	100.5
+ .00025	8.20	101.3	11.50	100.4	15.60	100.6	18.75	100.4	22.45	100.2
Flush	8.10	100.0	11.45	100.0	15.50	100.0	18.65	100.0	22.40	100.0
- .00025	8.05	99.4	11.45	100.0	15.40	99.3	18.50	99.2	22.25	99.3
- .00050	8.00	98.8	11.40	99.5	15.30	98.7	18.30	98.1	22.05	98.4
- .00075	8.00	98.8	11.30	98.7	15.15	97.7	18.05	96.8	21.80	97.3
- .00100	7.95	98.2	11.20	97.8	14.95	96.3	17.75	95.2	21.50	96.0
- .00150	7.85	96.9	11.00	96.0	14.45	93.2	17.05	91.4	20.75	92.7
- .00200	7.70	95.1	10.80	94.3	13.75	88.7	16.10	86.3	19.75	88.2
- .00250	7.40	91.4	10.50	91.7	13.10	84.5	15.10	80.9	18.65	83.2

EFFECT OF MISALIGNMENT ON BALANCE PERFORMACNE FOR SEVERAL REYNOLDS NUMBERS M = 2.67

TABLE III

Run	18		19		20		21		22	
Mach	2.62		2.65		2.68		2.68		2.69	
R_θ	4310		6900		10070		12940		15640	
Position	Force (Milli- pounds	Percent Level Value	F	%	F	%	F	%	F	%
+ .00300	8.20	118.0	11.85	119.7	16.35	120.2	20.90	119.7		
+ .00250	7.95	114.5	11.45	115.7	15.85	116.5	20.15	115.5	25.90	122.8
+ .00200	7.75	111.6	11.05	111.6	15.30	112.5	19.35	111.0	24.90	118.1
+ .00150	7.55	108.7	10.70	108.1	14.80	108.8	18.65	106.9	23.70	112.3
+ .00100	7.30	105.1	10.35	104.5	14.25	104.8	18.15	104.0	22.55	106.8
+ .00075	7.20	103.7	10.20	103.0	14.05	103.3	17.95	102.9	22.05	104.5
+ .00050	7.10	102.2	10.10	102.0	13.90	102.2	17.75	101.7	21.65	102.7
+ .00025	7.00	100.8	10.00	101.0	13.70	100.7	17.60	100.8	21.35	101.2
Flush	6.95	100.0	9.90	100.0	13.60	100.0	17.45	100.0	21.10	100.0
- .00025	6.90	99.3	9.80	99.0	13.45	98.8	17.30	99.1	20.95	99.2
- .00050	6.85	98.6	9.75	98.5	13.35	98.1	17.20	98.5	20.85	98.8
- .00075	6.80	97.9	9.70	98.0	13.30	97.8	17.10	98.0	20.75	98.3
- .00100	6.75	97.2	9.65	97.5	13.20	97.0	17.05	97.7	20.70	98.1
- .00150	6.65	95.7	9.50	95.9	13.05	95.9	17.00	97.4	20.60	97.6
- .00200	6.60	95.0	9.40	94.9	12.90	94.8	16.85	96.5	20.50	97.1
- .00250	6.55	94.3	9.25	93.4	12.80	94.1	16.50	94.5	20.30	96.2

EFFECT OF MISALIGNMENT ON BALANCE PERFORMANCE FOR SEVERAL REYNOLDS NUMBERS AT M = 3.15

TABLE IV

Run	23		24		25		26		27	
Mach	3.11		3.13		3.16		3.18		3.19	
R_θ	2970		5180		7180		9440		11880	
Position	Force (Milli-pounds)	Percent Level Value	F	%	F	%	F	%	F	%
+ .00300	6.35	116.6	8.35	115.2	10.20	117.2	12.75	118.1	15.05	115.8
+ .00250	6.10	112.0	8.20	113.2	10.05	115.5	12.35	114.3	14.70	113.1
+ .00200	5.95	109.2	8.00	110.3	9.75	112.1	11.95	110.7	14.20	109.2
+ .00150	5.80	106.5	7.80	107.7	9.45	108.7	11.60	107.3	13.80	106.1
+ .00100	5.70	104.7	7.55	104.2	9.15	105.2	11.25	104.2	13.45	103.5
+ .00075	5.65	103.7	7.45	102.8	9.05	104.1	11.10	102.8	13.30	102.3
+ .00050	5.60	102.8	7.40	102.2	8.90	102.3	10.95	101.3	13.15	101.2
+ .00025	5.50	101.0	7.30	100.7	8.80	101.2	10.85	100.4	13.10	100.7
Flush	5.45	100.0	7.25	100.0	8.70	100.0	10.80	100.0	13.00	100.0
- .00025	5.35	98.2	7.15	98.7	8.65	99.4	10.75	99.5	13.00	100.0
- .00050	5.25	96.3	7.10	97.9	8.65	99.4	10.70	99.0	12.90	99.2
- .00075	5.15	94.5	7.00	96.6	8.60	98.8	10.65	98.6	12.85	98.8
- .00100	5.05	92.7	6.95	95.8	8.55	98.2	10.60	98.1	12.75	98.0
- .00150	4.95	90.8	6.80	93.8	8.40	96.6	10.50	97.2	12.50	96.2
- .00200	4.85	89.0	6.65	91.8	8.20	94.2	10.30	95.3	12.20	93.8
- .00250	4.85	89.0	6.60	91.1	8.05	92.5	10.05	93.0	11.80	90.7

EFFECTS OF MISALIGNMENT ON BALANCE PERFORMANCE FOR SEVERAL REYNOLDS NUMBERS AT M = 3.55

TABLE V

Run	6		7		8		9	
Mach	3.45		3.59		3.49		3.62	
R_θ	3640		6590		8670		9980	
Position	Force (Milli-pounds)	Percent Level Value	F	%	F	%	F	%
+ .0030	4.80	111.7			7.70	115.0	8.95	114.8
+ .00250	4.65	108.2	6.40	111.3	7.50	112.0	8.60	110.3
+ .00200	4.55	105.9	6.25	108.8	7.30	109.0	8.35	107.1
+ .00150	4.50	104.7	6.10	106.2	7.15	106.8	8.20	105.2
+ .00100	4.50	104.7	5.95	103.6	7.05	105.2	8.10	103.9
+ .00075	4.45	103.5	5.90	102.7	7.00	104.5	8.00	102.6
+ .00050	4.40	102.4	5.85	101.8	6.90	103.1	7.95	102.0
+ .00025	4.35	101.2	5.80	101.0	6.80	101.6	7.90	101.3
Flush	4.30	100.0	5.75	100.0	6.70	100.0	7.80	100.0
- .00025	4.25	98.8	5.65	98.2	6.65	99.3	7.75	99.3
- .00050	4.20	97.7	5.55	96.5	6.60	98.5	7.70	98.8
- .00075	4.15	96.5	5.50	95.6	6.55	97.8	7.65	98.1
- .00100	4.05	94.2	5.45	94.8	6.45	96.3	7.60	97.4
- .00150	3.95	91.9	5.35	93.0	6.35	94.8	7.45	95.5
- .00200	3.85	89.5	5.30	92.2	6.25	93.3	7.30	93.5
	3.85	89.5	5.30	92.2	6.15	91.8	7.10	91.0

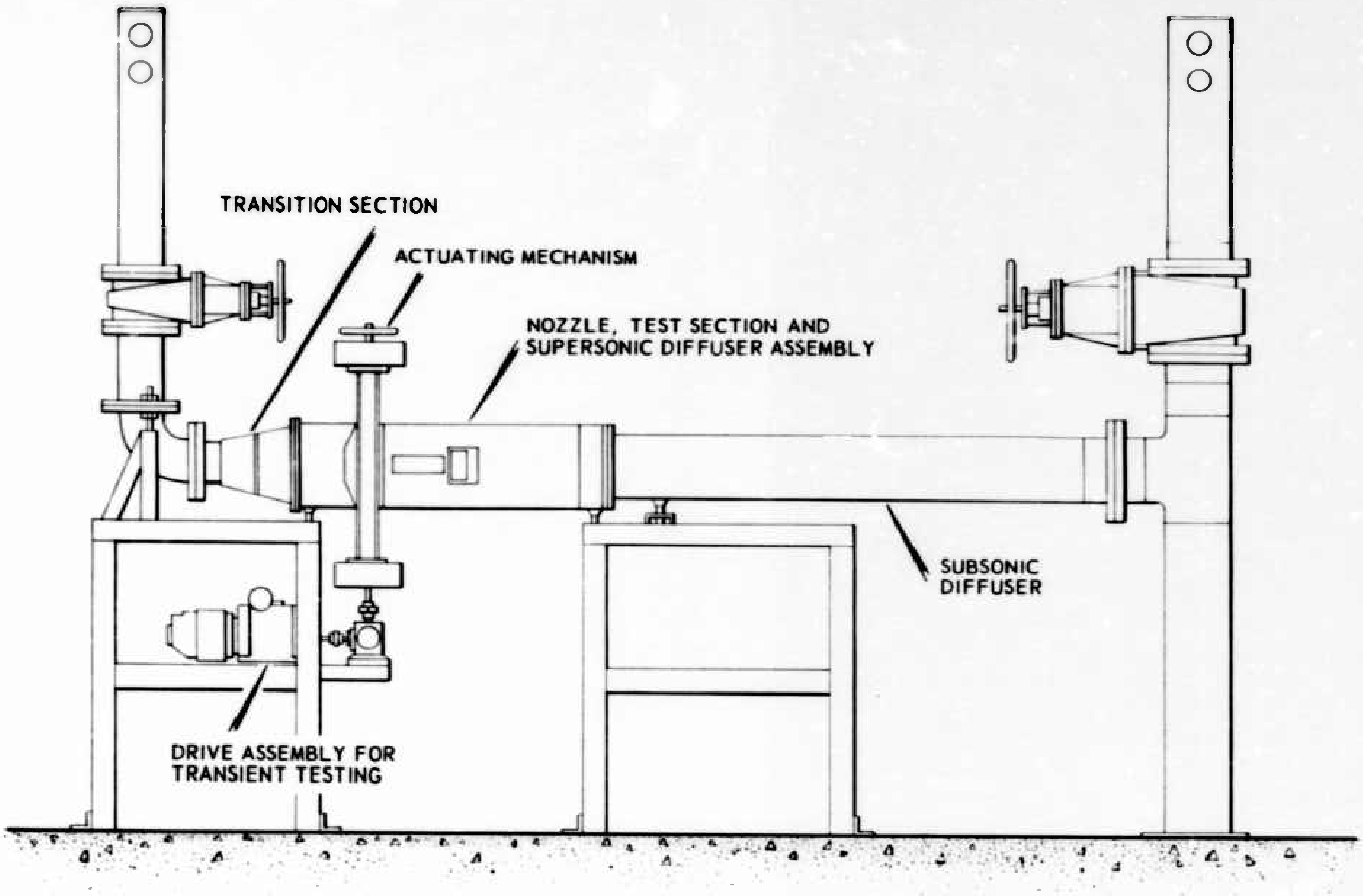

FIGURE 1
VARIABLE MACH NUMBER WIND TUNNEL INSTALLATION

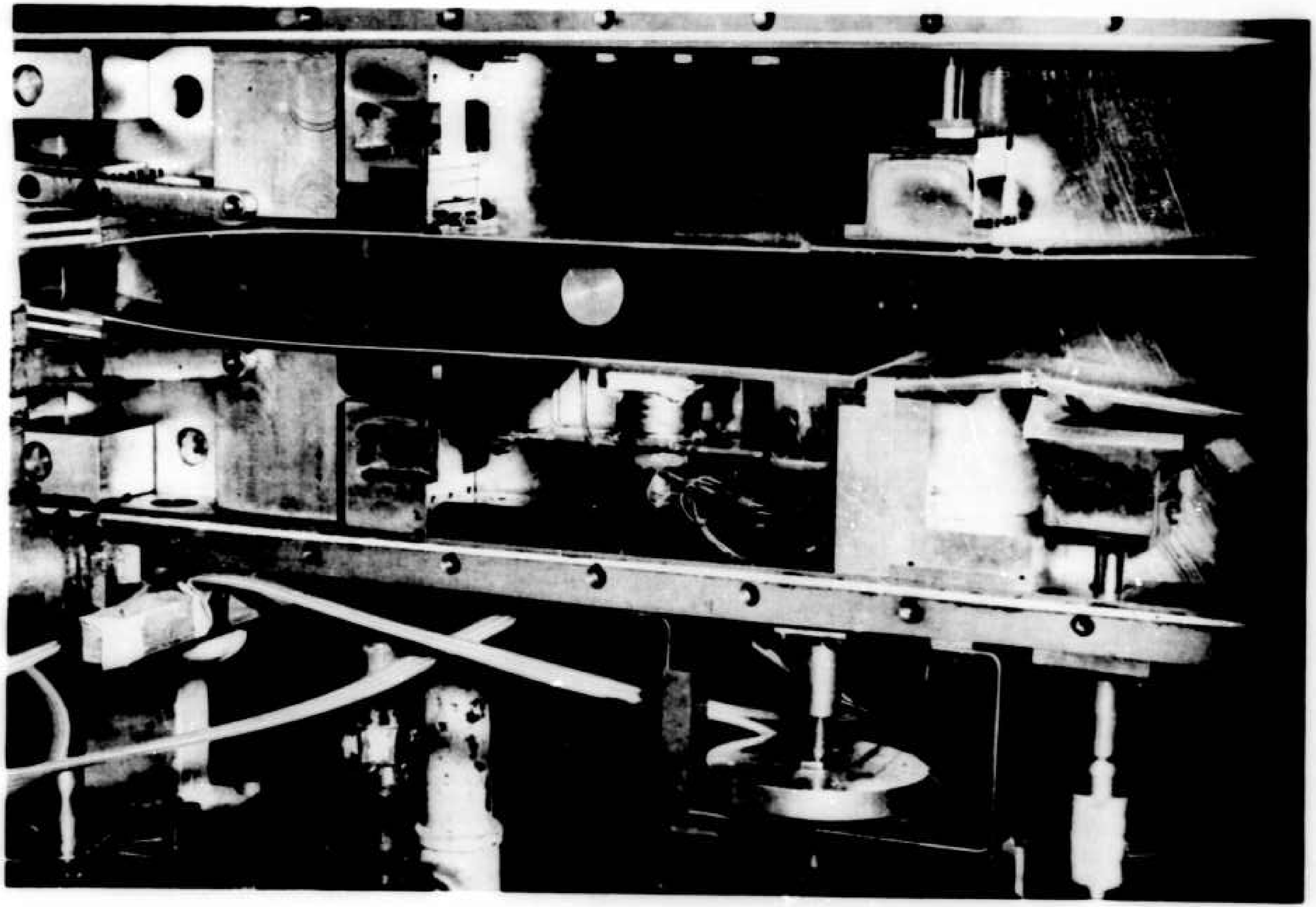

FIGURE 2
TEST SECTION OF VARIABLE MACH NUMBER WIND TUNNEL WITH SKIN FRICTION BALANCE ELEVATION MECHANISM IN PLACE

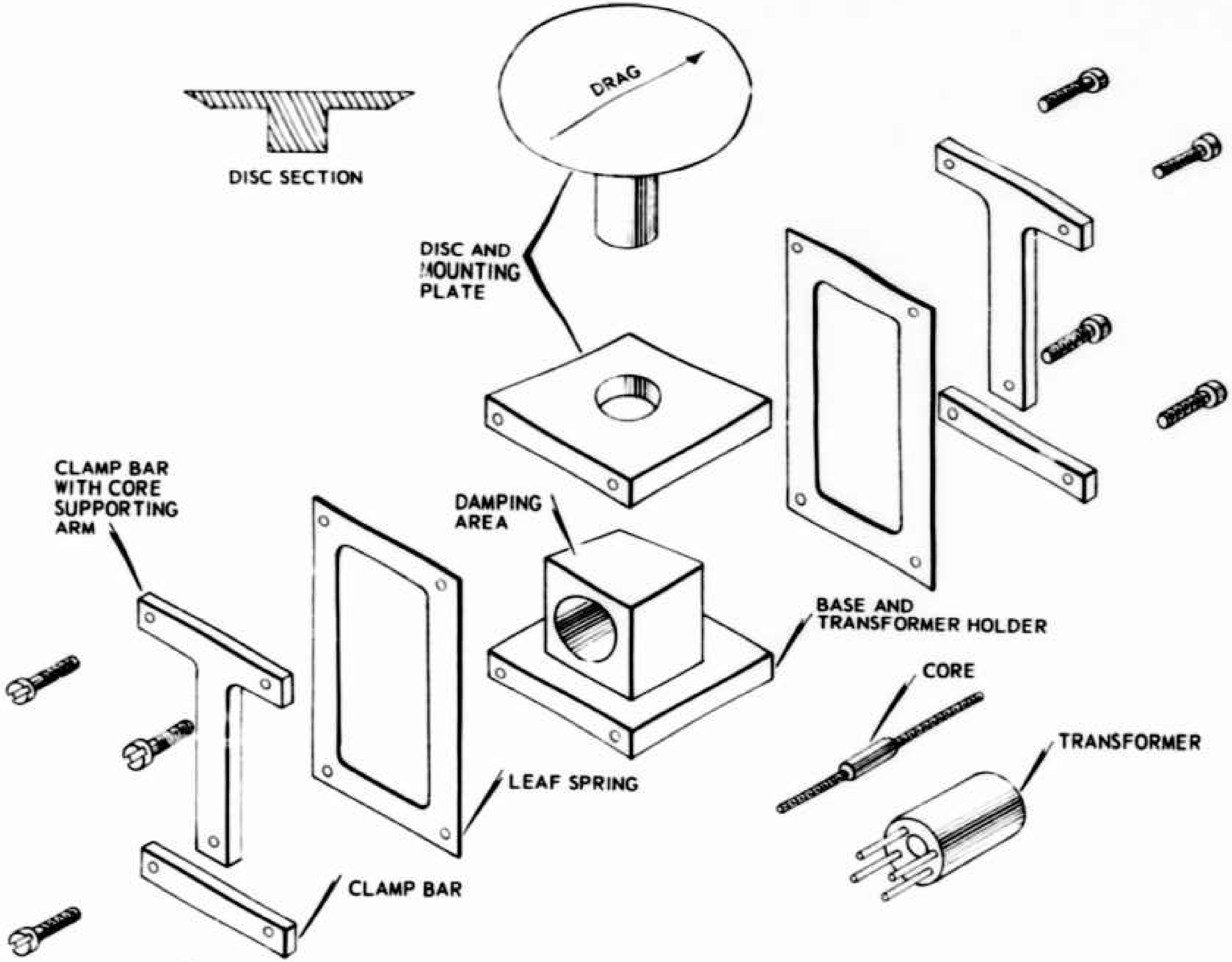

FIGURE 3
EXPLODED VIEW OF SKIN FRICTION BALANCE

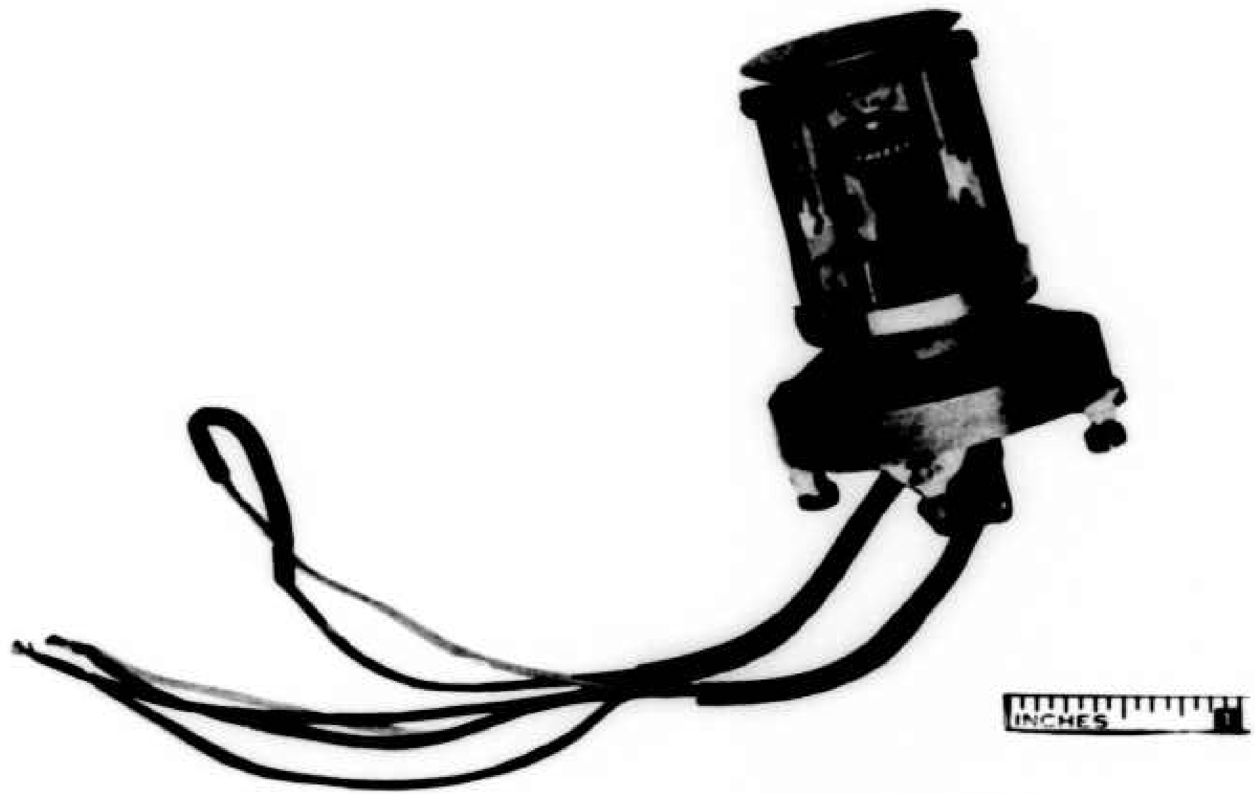

FIGURE 4
INTERNAL MECHANISM OF SKIN FRICTION BALANCE

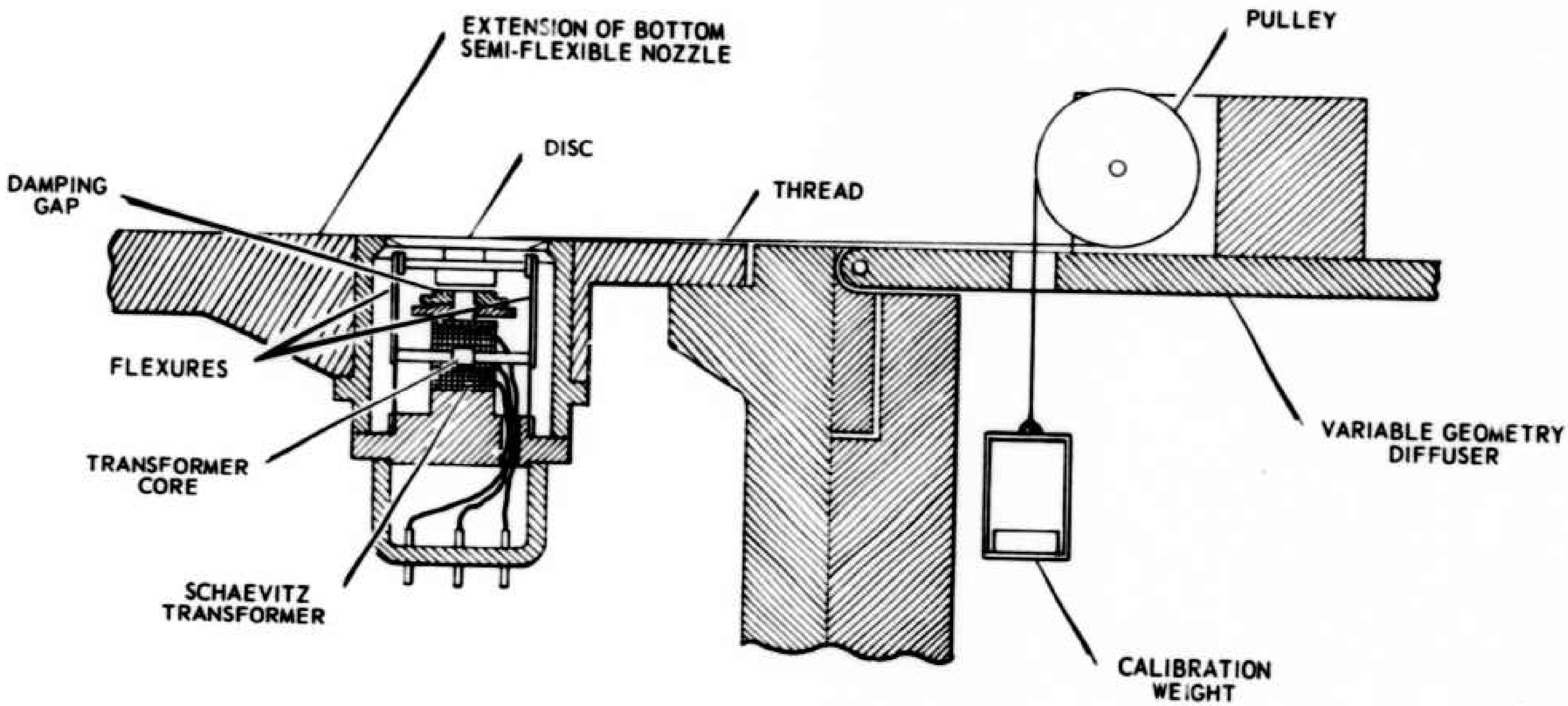

FIGURE 5
SCHEMATIC DIAGRAM OF SKIN FRICTION BALANCE AND CALIBRATOR

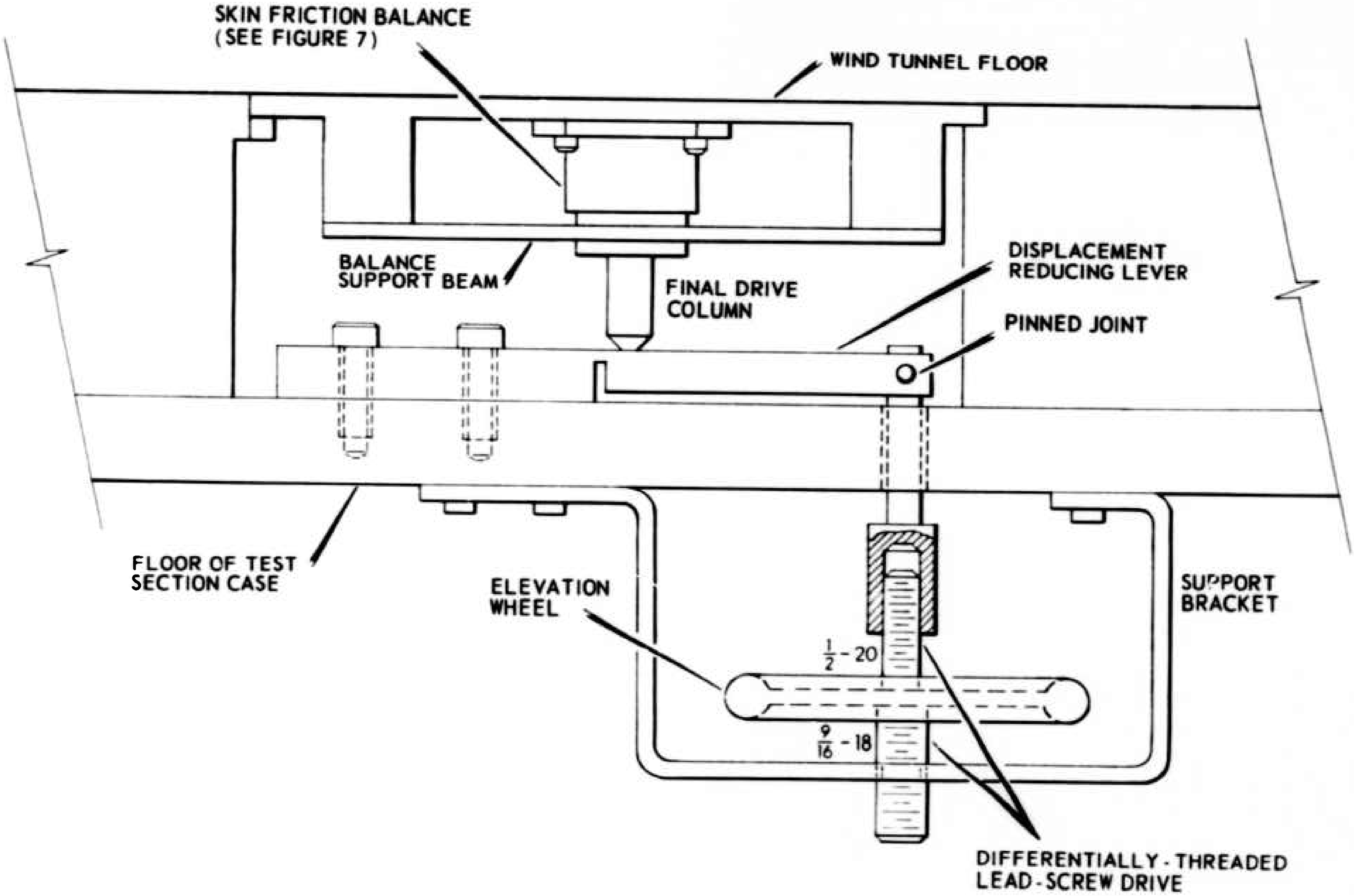

FIGURE 6
SKIN FRICTION BALANCE
ELEVATION MECHANISM

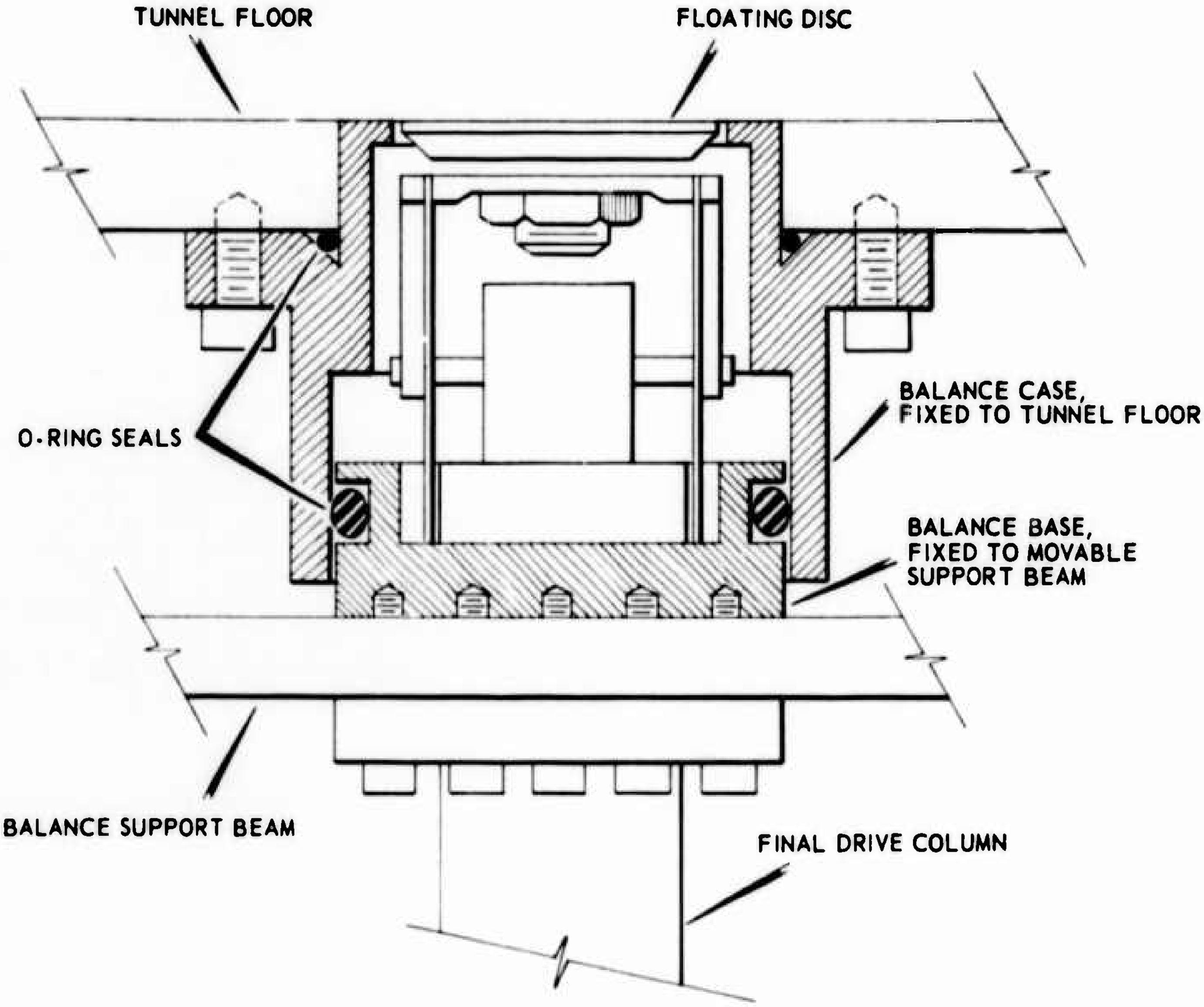

FIGURE 7
DETAILED VIEW OF SKIN FRICTION
BALANCE MOUNTING ARRANGEMENT

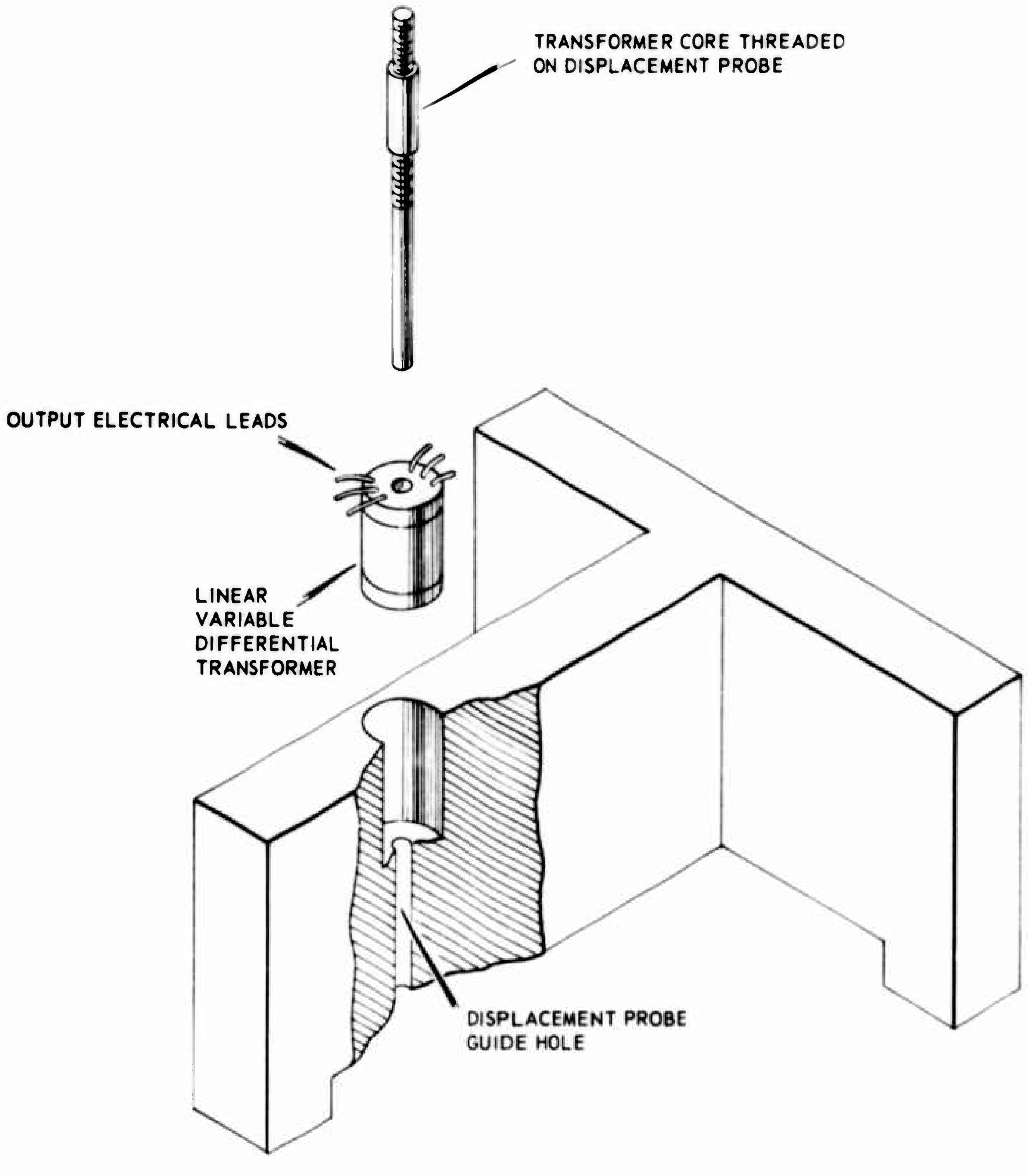

FIGURE 8
EXPLODED VIEW OF DISPLACEMENT GAGE

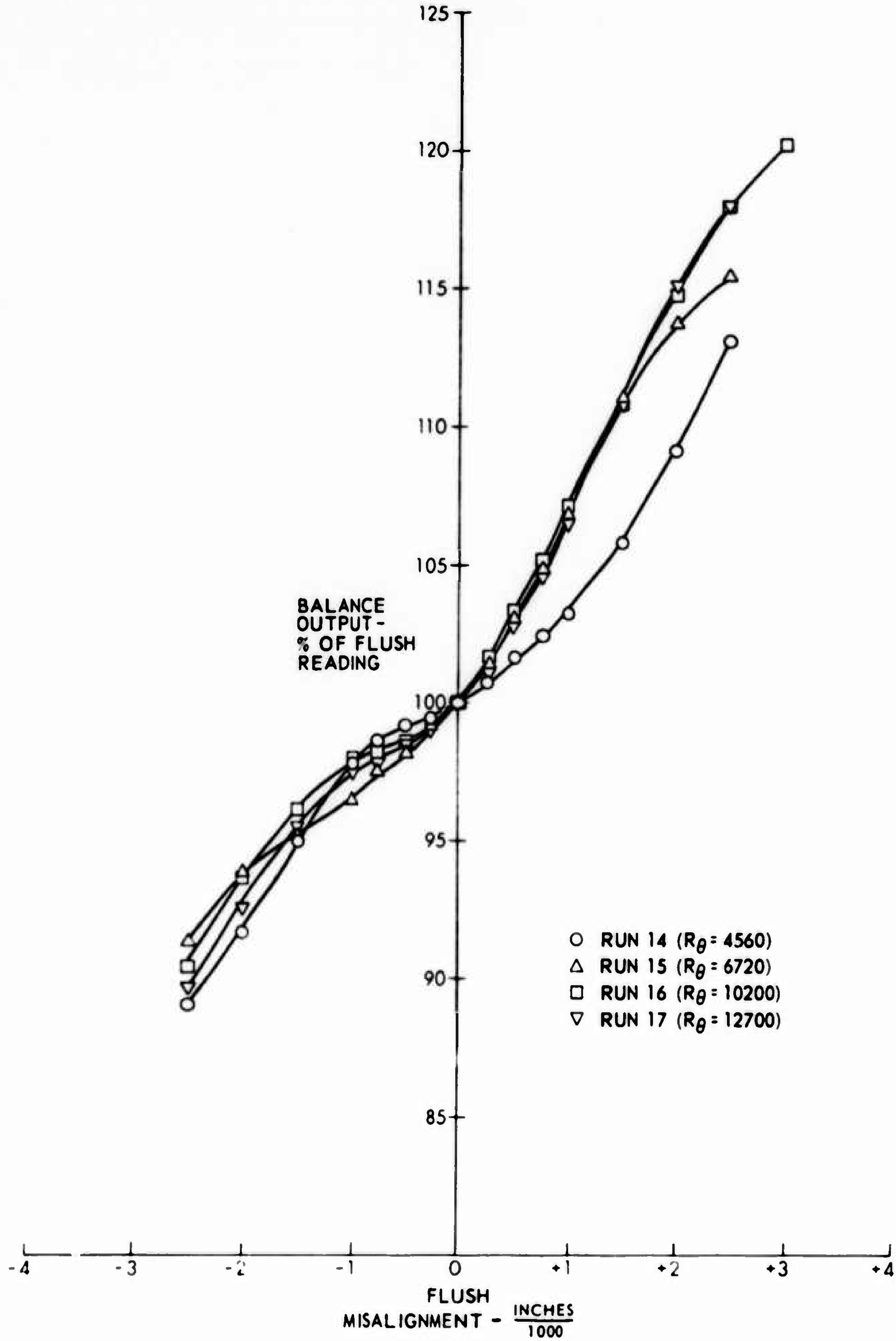

FIGURE 9
EFFECT OF MISALIGNMENT FOR SEVERAL REYNOLDS NUMBERS AT M = 1.73

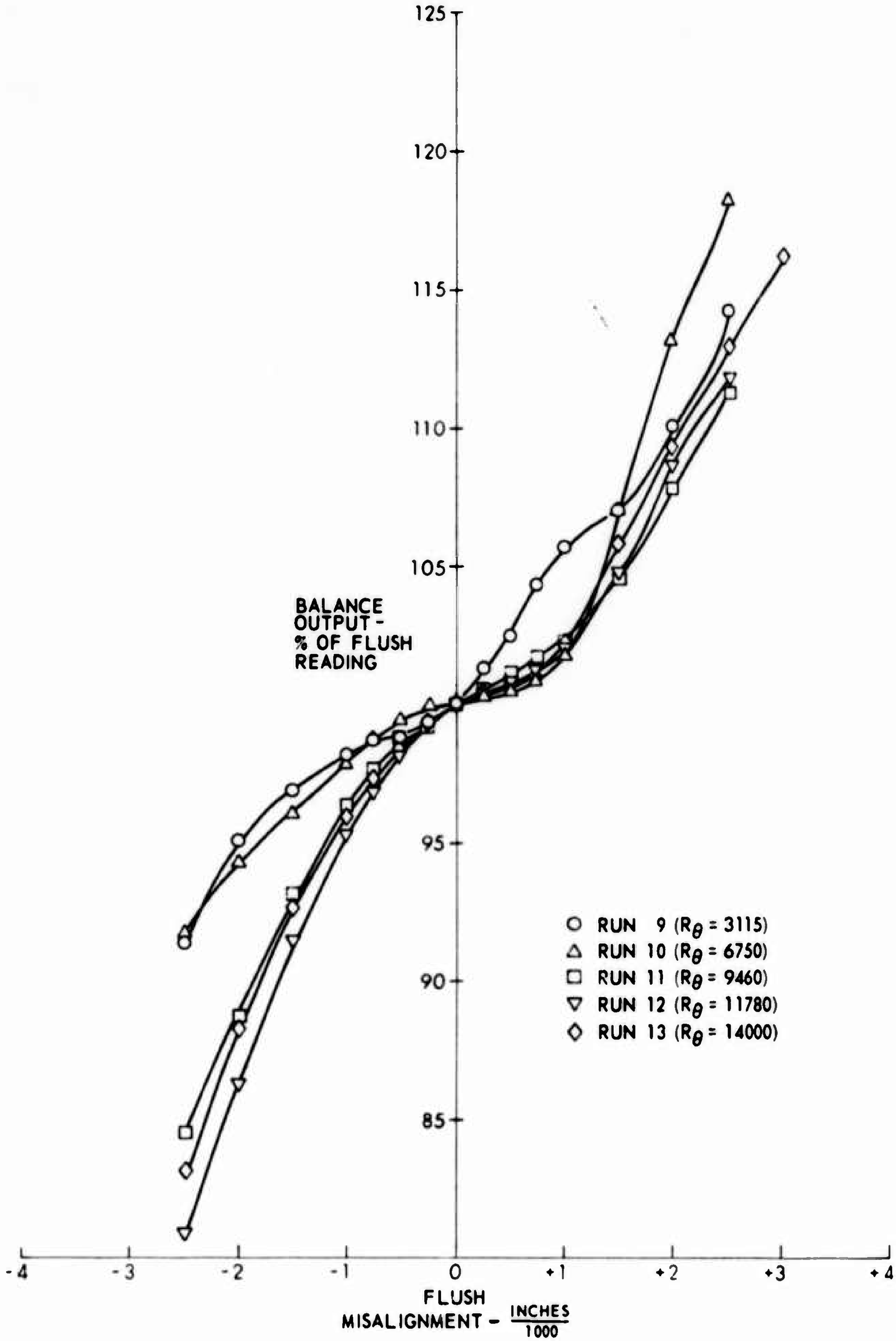

FIGURE 10
EFFECT OF MISALIGNMENT FOR SEVERAL REYNOLDS NUMBERS AT M = 2.23

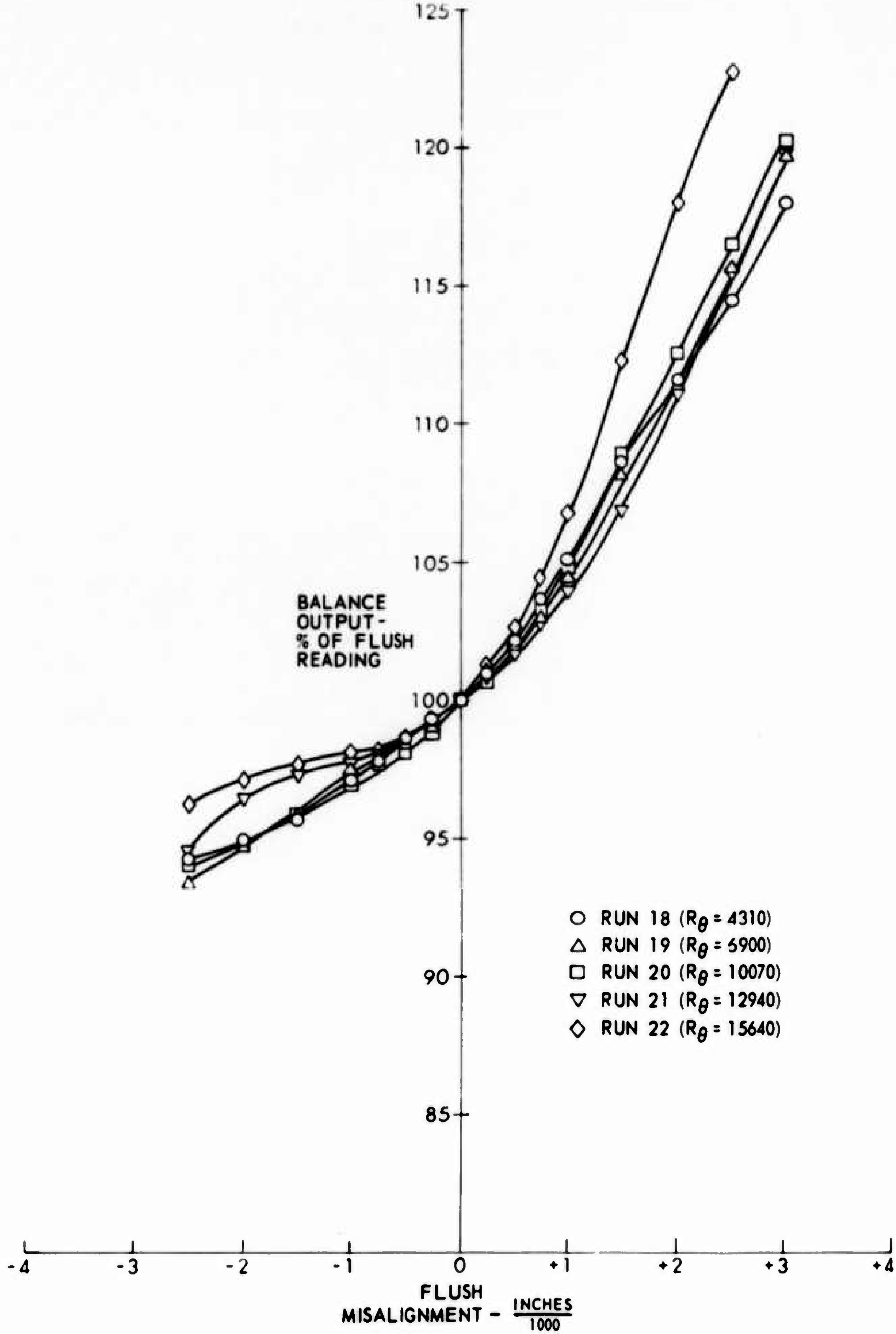

FIGURE 11
EFFECT OF MISALIGNMENT FOR SEVERAL REYNOLDS NUMBERS AT M = 2.67

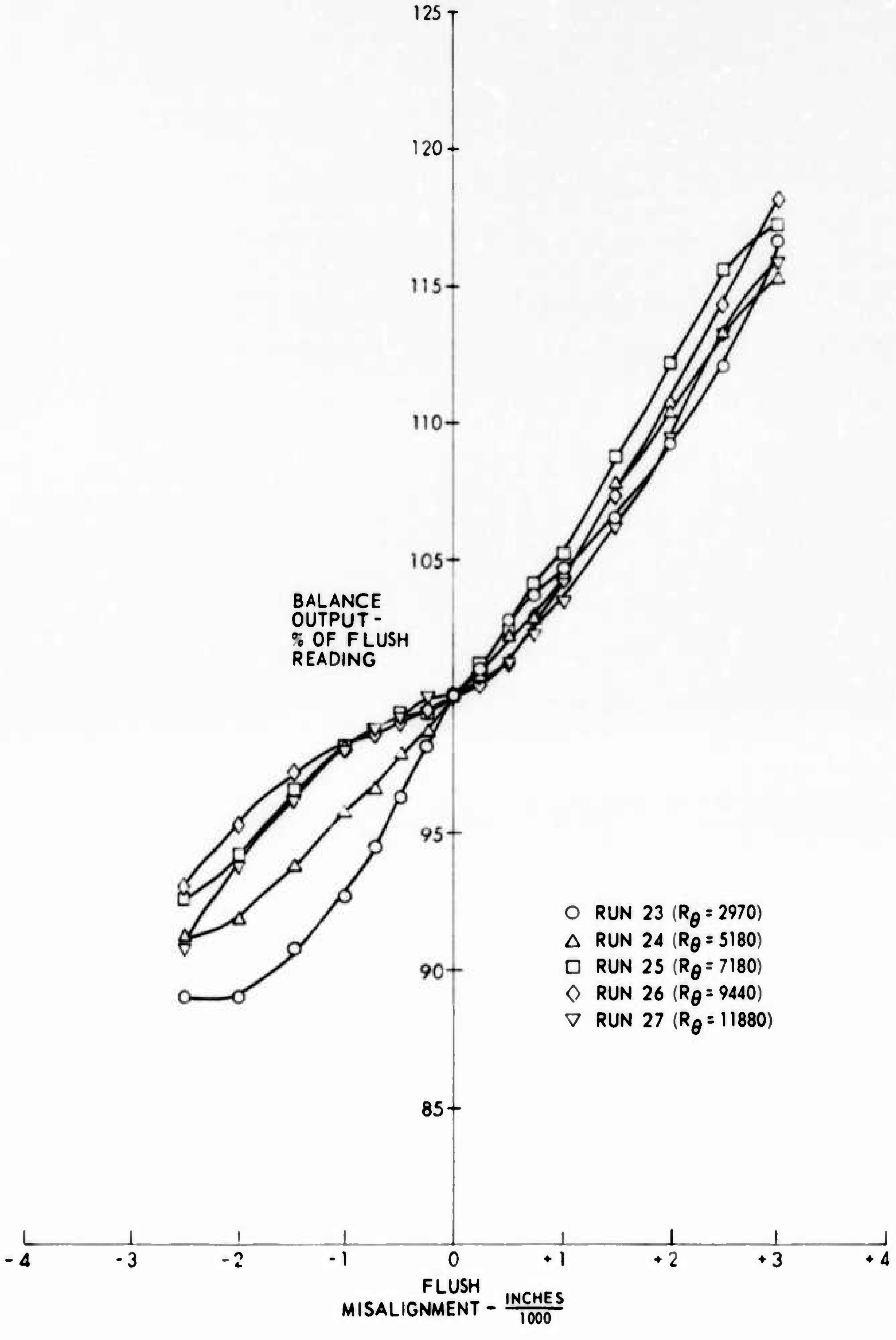

FIGURE 12
EFFECT OF MISALIGNMENT FOR SEVERAL REYNOLDS NUMBERS AT M = 3.15

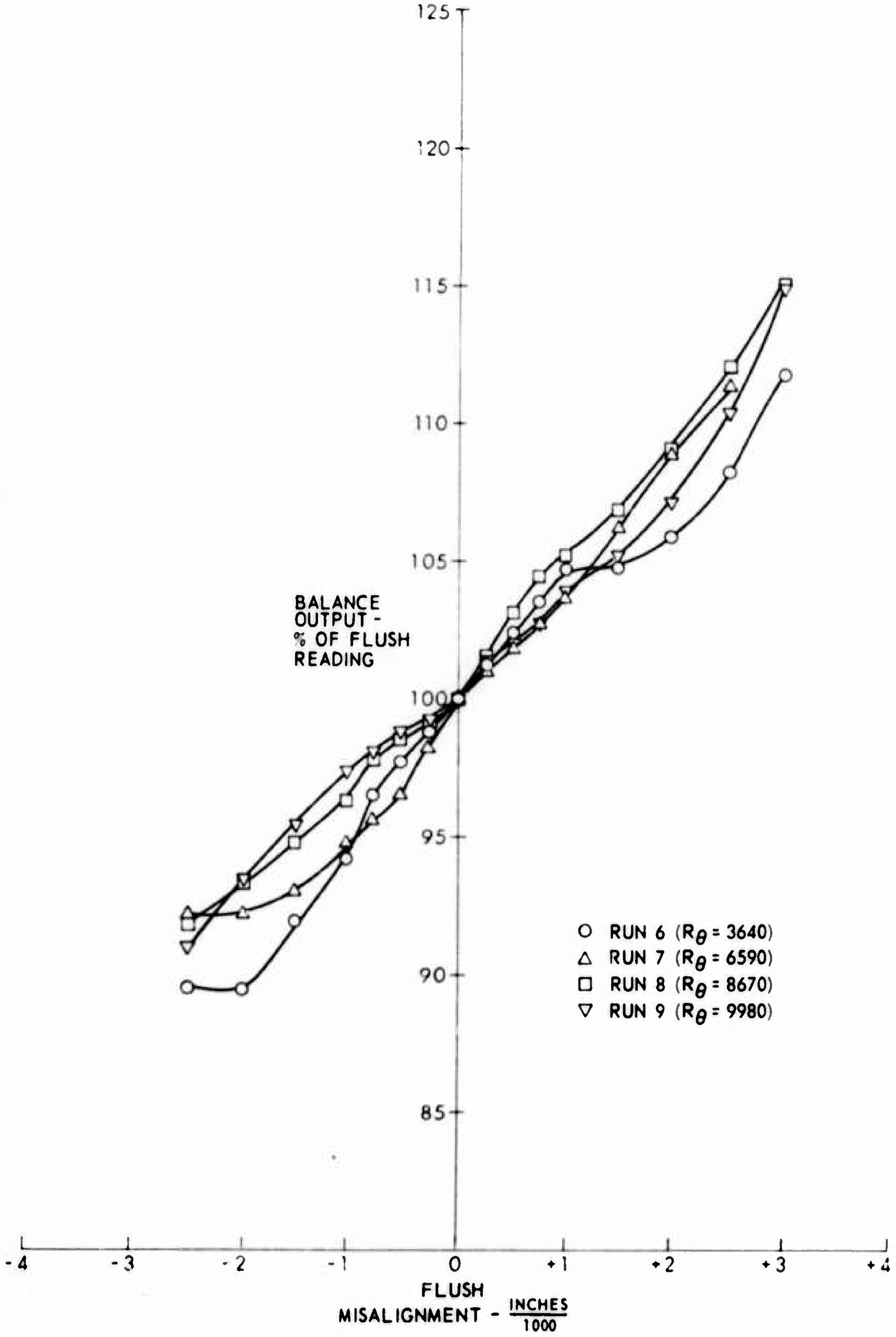

FIGURE 13
EFFECT OF MISALIGNMENT FOR SEVERAL REYNOLDS NUMBERS AT M = 3.55

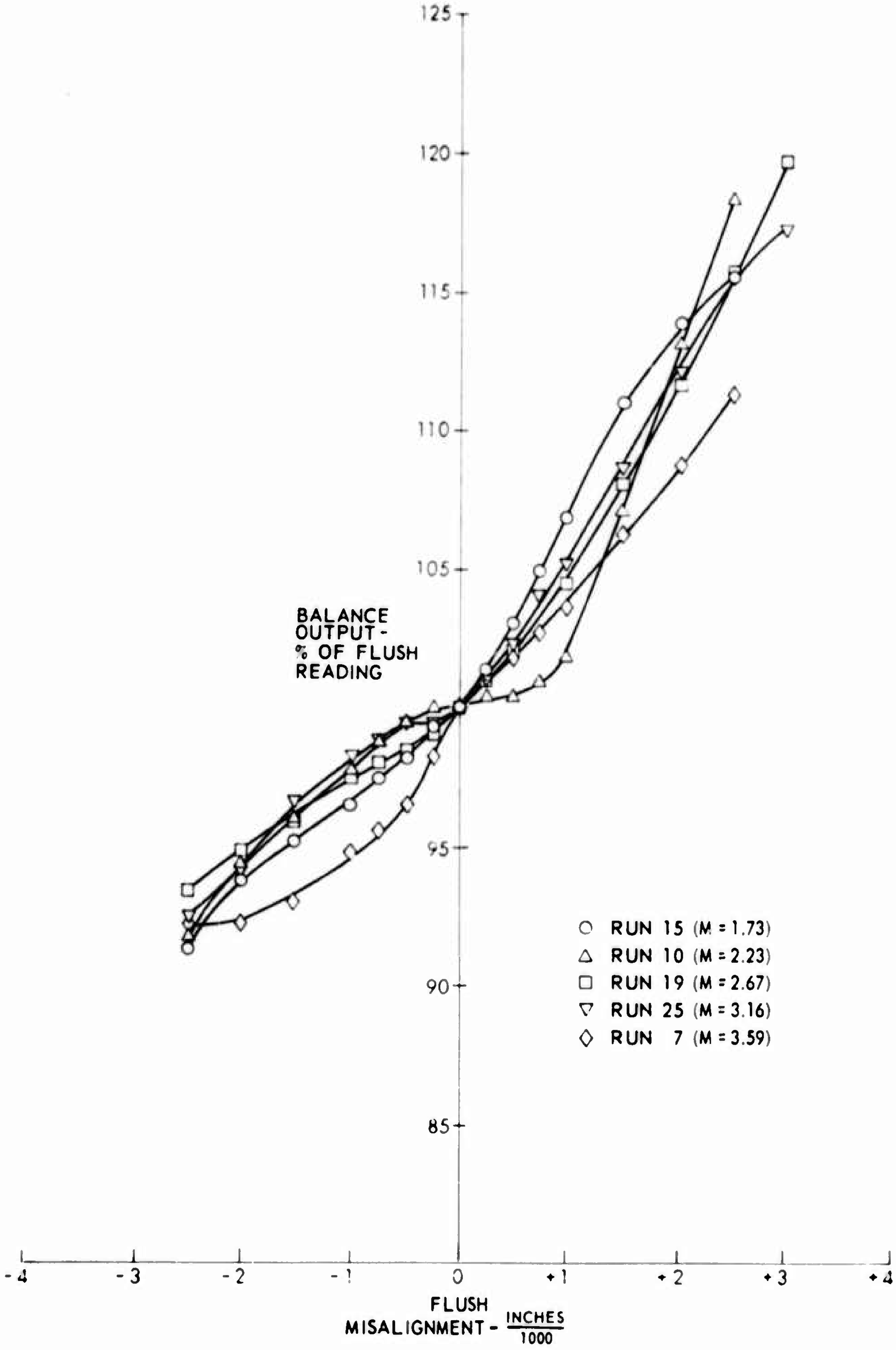

FIGURE 14
EFFECT OF MISALIGNMENT FOR SEVERAL MACH NUMBERS AT R_θ = 6790

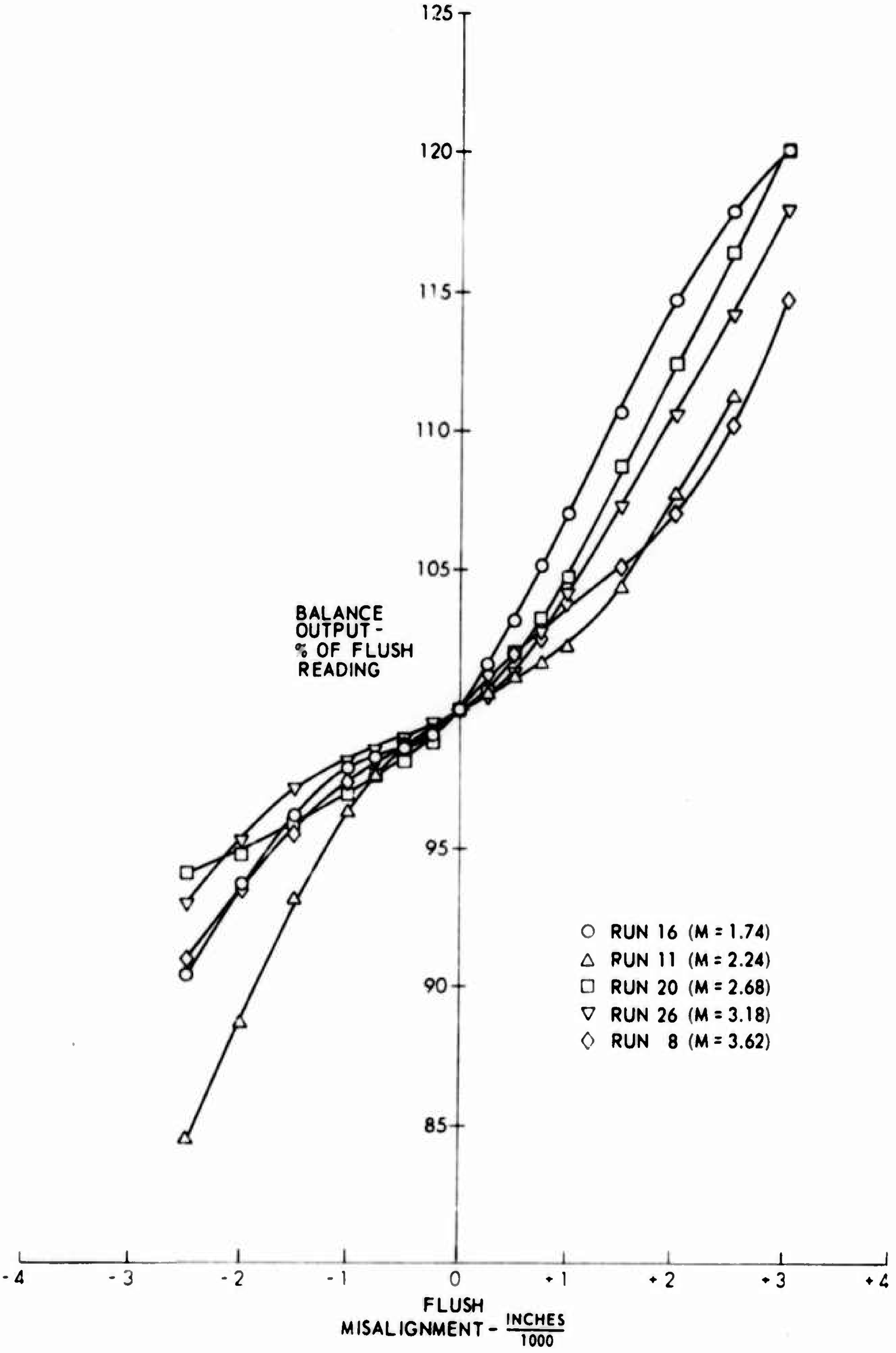

FIGURE 15
EFFECT OF MISALIGNMENT FOR SEVERAL MACH NUMBERS AT R_θ=9830

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